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Spatial patterns and recent trends in the climate of tropical rainforest regions

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We present an analysis of the mean climate and climatic trends of tropical rainforest regions over the period 1960–1998, with the aid of explicit maps of forest cover and climatological databases. Until the mid-1970s most regions showed little trend in temperature, and the western Amazon experienced a net cooling probably associated with an interdecadal oscillation. Since the mid-1970s, all tropical rainforest regions have experienced a strong warming at a mean rate of 0.26 ± 0.05 °C per decade, in synchrony with a global rise in temperature that has been attributed to the anthropogenic greenhouse effect. Over the study period, precipitation appears to have declined in tropical rainforest regions at a rate of $1.0 \pm 0.8\%$ per decade ($p < 5\%$), declining sharply in northern tropical Africa (at 3–4% per decade), declining marginally in tropical Asia and showing no significant trend in Amazonia. There is no evidence so far of a decline in precipitation in eastern Amazonia, a region thought vulnerable to climate-change-induced drying. The strong drying trend in Africa suggests that this should be a priority study region for understanding the impact of drought on tropical rainforests. We develop and use a dry-season index to study variations in the length and intensity of the dry season. Only African and Indian tropical rainforests appear to have seen a significant increase in dry-season intensity. In terms of interannual variability, the El Niño–Southern Oscillation (ENSO) is the primary driver of temperature variations across the tropics and of precipitation fluctuations for large areas of the Americas and southeast Asia. The relation between ENSO and tropical African precipitation appears less direct.

Keywords: tropical forest; Amazonia; Africa; Asia; climate change; drought

1. INTRODUCTION

The global atmosphere is undergoing a period of rapid human-driven change, with no historical precedent in either its rate of change or its potential absolute magnitude (IPCC 2002). There is considerable concern at how this change may affect the Earth's ecosystems, and in turn how these system responses may feed back to accelerate or decelerate global change. This threat is spawning considerable laboratory and field research into ecosystem responses to climate. This research gains its justification by the global change agenda. However, there is a gap here between global context and local research that can sometimes feel unsatisfactory.

Global warming trends over the twentieth century have been examined comprehensively at global or regional levels (e.g. Jones *et al.* 1999; Giorgi 2002; New *et al.* 2001), particularly through the work of the IPCC (e.g. Folland *et al.* 2002). Among other issues, this has prompted concern at how ecosystems may respond to such trends. Yet, there have been few attempts to examine climate trends at the level of specific biomes, and in particular the tropical rainforest biome.

By contrast, there has recently been a surge in research aimed at understanding the interactions between climate change and tropical rainforest ecology and function, which is reflected in several of the papers in this thematic issue (Baker *et al.* 2004; Chambers & Silver 2004; Clark 2004; Körner 2004; Lewis *et al.* 2004*b*; Phillips *et al.* 2004). However, in justification of their research agenda, tropical forest researchers have usually needed to rely on broad or global climatic trends reported by the IPCC, or generalities about warming or drying climates. However, what are the recent trends in the climate of the region or biome being studied, and how do these trends compare with general trends in tropical rainforest regions and with projections from global climate models?

Furthermore, studies are frequently focused at one field site, and, without knowing the environmental context of that field site, it can be difficult to infer wider conclusions about the entire tropical rainforest biome (Malhi *et al.* 2002*b*). How does the climate of a particular site or region (in terms of mean state, seasonality and interannual variability) fit into the climatic context of tropical rainforests as a whole?

Our intention is to address the gap we perceive is present in the literature. However, a primary problem facing any climate trend analysis in tropical forest regions is a relative paucity of meteorological data and very few long-term records. In this analysis, we concentrate primarily on climatic trends since 1960. Over this short timescale it can be difficult to ascribe any observed local trends

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One contribution of 17 to a Theme Issue 'Tropical forests and global atmospheric change'.

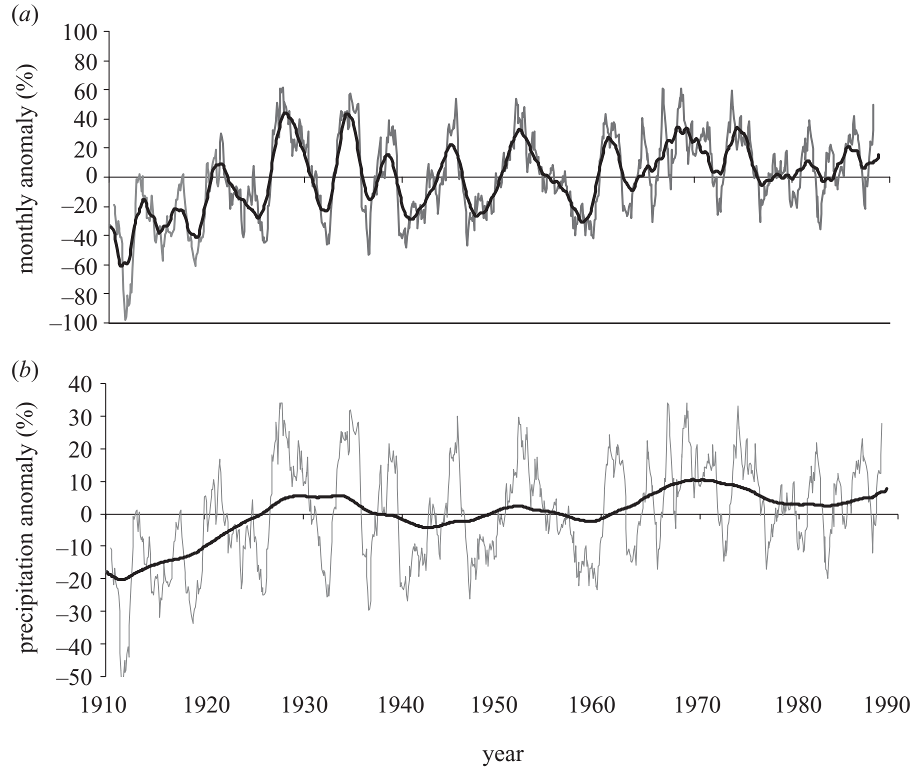


Figure 1. Monthly precipitation anomaly at Manaus over the twentieth century, smoothed with a 12-month moving average; (*a*) with the first two components of a singular spectral analysis (a 6–8 year oscillation and a 20 year oscillation) superposed; (*b*) with only the net trend and 20 year oscillation superposed. Much of the interannual variability can be explained by these two oscillations.

to long-term trend or short-term fluctuation. In relation to the papers in this thematic issue, this focus on recent climate helps put any discussion of recent observed changes in tropical rainforests (Baker *et al.* 2004; Lewis *et al.* 2004*a*; Phillips *et al.* 2004) into a climatological context. Independent of their causes, climate trends and extremes of the past 40 years are the ones that will have the most direct effect on the structure and dynamics of the tropical rainforests of today.

We also use recent global climatic datasets to examine the spatial variability of tropical rainforest climates. In public imagination, the climate of the tropical rainforest is frequently characterized as 'ever-warm and ever-wet'. In reality, however, although the 'ever-warm' is generally true (but not always), tropical rainforest regions can span a wide range of intensity and seasonality of rainfall. Moreover, many regions can experience significant interannual, interdecadal and perhaps intercentennial variability in rainfall, and the regularity and intensity of drought can have a major impact on forest structure and adaptation. In the face of this spatial heterogeneity, there can be a danger of extrapolating too much from intensive studies of tropical rainforest in one locale; thus a global synthesis of tropical rainforest climate helps put the climate of any particular site into context. The new global observational climatologies can be a powerful tool with which to address questions in tropical rainforest ecology.

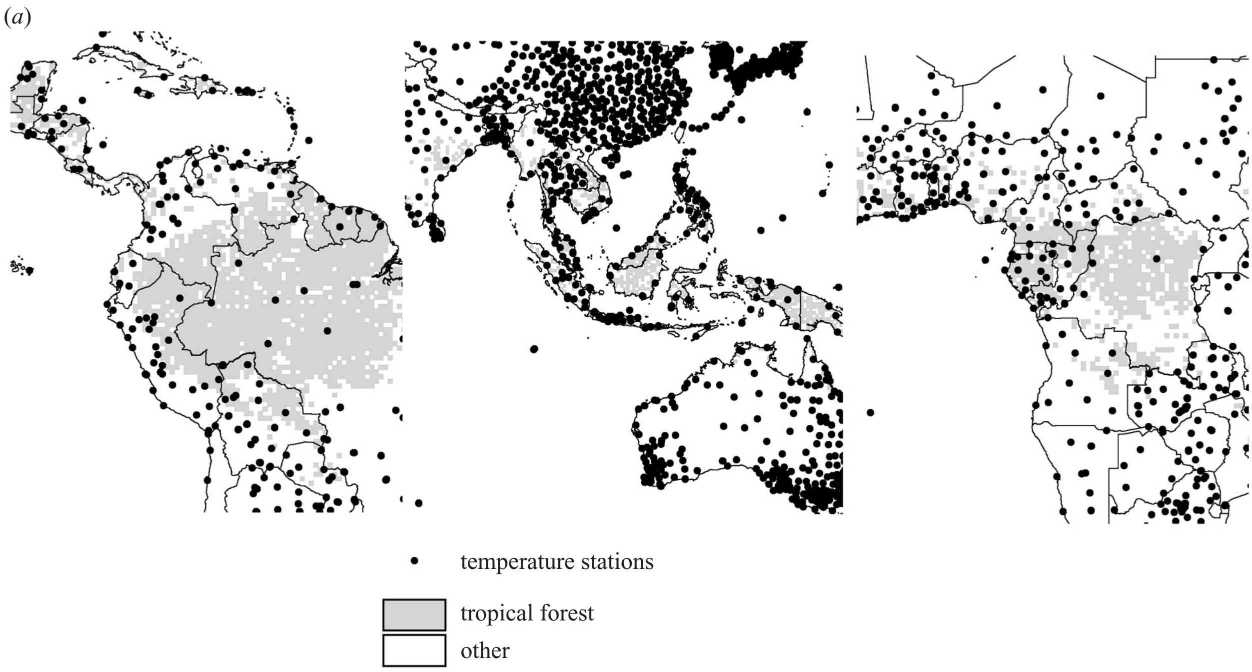
We focus on three climatic parameters: temperature, precipitation and dry-season intensity. There are other atmospheric parameters, which vary and may have a direct effect on tropical forests, the principal examples being carbon dioxide concentrations, direct and diffuse solar radiation, and nitrogen deposition. Their possible influences are reviewed in a companion paper in this thematic issue (Lewis *et al.* 2004*b*). We also examine in particular detail the role of the ENSO, which is the primary driver of interannual climate variability in the tropics.

We address the following questions.

(i) What do these recent climatic datasets tell us about the spatial heterogeneity of the tropical rainforest climate and the representativeness of particular study regions?
(ii) How is interannual variability in temperature, precipitation and drought stress in different regions related to the ENSO, the primary driver of present-day climatic variability in the tropics?
(iii) What are the trends in temperature, precipitation and drought stress in the past 40 years, and how do we interpret these trends in terms of possible artefacts, longer-term oscillations and net anthropogenic trends?

2. THE EL NIÑO–SOUTHERN OSCILLATION

The major agent of interannual climatic variability in many of the tropical rainforest regions is the ENSO (see figures 4, 5, 10 and 11), a 3–5 year oscillation of sea-surface temperature and atmospheric pressure patterns in the equatorial Pacific Ocean. Any net shift in El Niño frequency or intensity could have a greater impact on tropical rainforests than a gradual long-term trend in climate. How likely is such a change?



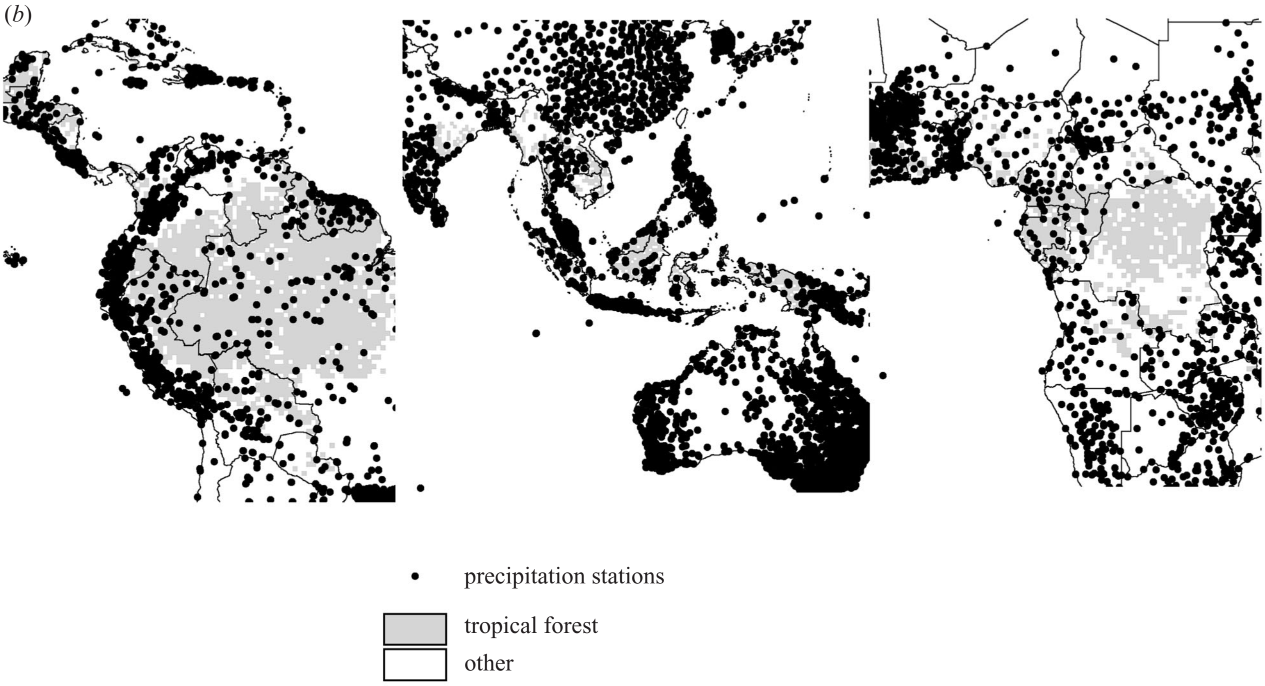


Figure 2. A map of (*a*) temperature stations and (*b*) precipitation stations used in this analysis. Many of these stations were present for only part of the period 1960–1998, as detailed in the text. Climatic means were interpolated from a denser network of stations. Some outlying regions are not shown in subsequent maps but are included in the analysis.

ENSO is an internal atmospheric–ocean oscillation that can show dramatic and nonlinear responses to subtle changes in driving variables, which makes it notoriously difficult to simulate accurately in climate models. By contrast, evidence from coral cores (Tudhope *et al.* 2001) shows that it was still very apparent in the last ice age, when global conditions were very different. There is evidence (Tudhope *et al.* 2001) of a gradual increase in El Niño intensity in recent millennia, associated with a 20 000 year precession in the seasonal timing of perihelion (when the Earth is closest to the sun). The amplitude of the oscillation appears to have been stronger in the early twentieth century, and then weakened over the period 1920–1960, before strengthening sharply since the 1960s. This variation in amplitude does not seem attributable to any simple direct cause, and may simply reflect an internal oscillation. There appears to have been a climate 'shift' in the tropical Pacific around 1976, and the frequency and intensity of ENSO has been unusual since 1976 compared with the previous 100 years. Warm phase ENSO (El Niño) episodes have been relatively more frequent, persistent or intense than the opposite cold phase (La Niña)

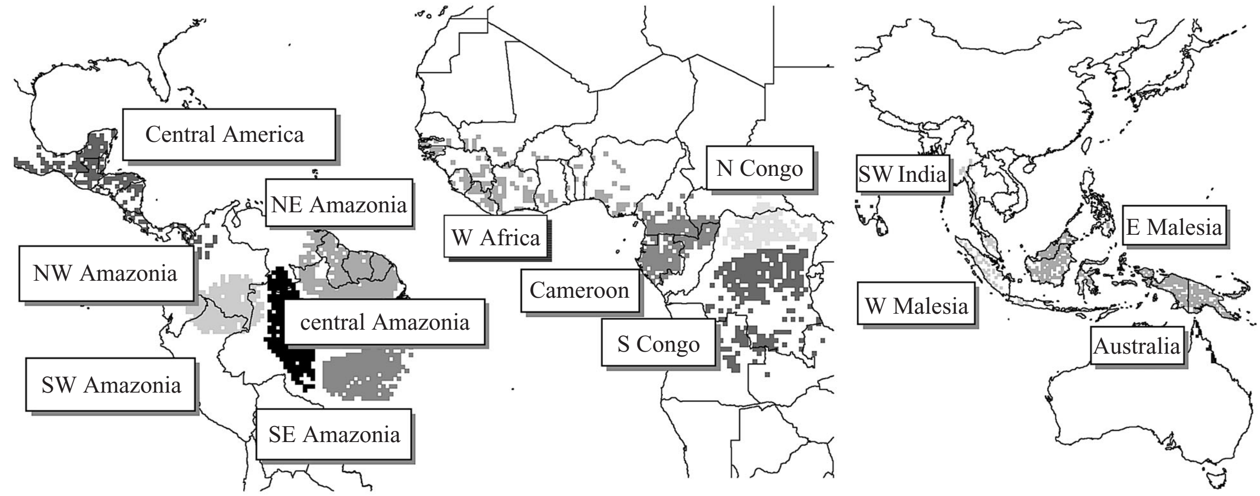


Figure 3. A map of the tropical rainforest subregions allocated for this analysis. Names of subregions are convenient geographical descriptors rather than reflecting political identities.

during this period. The two most severe El Niño events in the 100 years of instrumental records were in 1982–1983 and 1997–1998. This tropical Pacific warming may be related to anthropogenic forcing (Knutson & Manabe 1998), but mechanistic understanding of the natural multidecadal variability of ENSO is still poor.

There have been significant improvements in climate model simulation of ENSO (McAvaney *et al.* 2002), but there remains disagreement between models as to how ENSO will respond to anthropogenic climate change. Most, though not all, climate models indicate a net shift of the equatorial Pacific towards an El Niño-like mean state (Cubasch *et al.* 2002), but for a variety of physical reasons that are not consistent between models. There is little agreement among climate models as to whether the El Niño extremes of the oscillation will increase in intensity and frequency in response to anthropogenic warming.

We will examine the relation between ENSO and tropical rainforest temperatures and precipitation over the period 1960–1998. We employ a multivariate ENSO index, which combines data on sea-level pressure, surface winds, surface air temperature and total cloud cover in the tropical Pacific (Wolter & Timlin 1993; available at www.cdc.noaa.gov).

3. AN ANALYSIS OF VARIATION OF TEMPERATURE, PRECIPITATION AND DRY-SEASON INTENSITY IN TROPICAL RAINFOREST REGIONS IN THE LATE TWENTIETH CENTURY: METHODS

The main focus of this paper is an analysis over tropical rainforest regions of temporal trends in temperature, precipitation and dry-season strength over the late twentieth century (1960–1998), and of the spatial variability of these trends.

Before embarking on this analysis, we emphasize one important caveat: the ocean–atmosphere system may exhibit several multi-decadal internal oscillations, and trends observed over a 39 year period may not reflect longer-term variations. Hence, caution must be applied in attributing these short-term changes to a longer-term trend caused by anthropogenic influences.

Figure 1 shows an example of this problem, showing measurements of the precipitation anomaly from Manaus in the central Brazilian Amazon (one of the oldest climatological stations in the deep tropics) over the period 1910–1990. The time-series shown is of deseasonalized monthly precipitation anomalies, smoothed with a 12 month moving average. A clear feature in the time-series is the presence of strong coherent oscillations at multi-annual scales. A singular spectral analysis of this variation (dark solid lines), shows a dominant short-term oscillation on 6–8 year time-scales (figure 1*a*), but also evidence of a 20 year oscillation superposed on a net century-scale increase (figure 1*b*). This 20 year oscillation in Amazon precipitation was also reported by Botta *et al.* (2002).

Over the full 80 year period Manaus has shown a gradual increase in precipitation at a rate of 56 ± 25 mm per decade, or $2.6 \pm 1.2\%$ per decade, much of it in the first few decades of the century. Over the period 1960–1990, however, Manaus showed no significant change in precipitation ($-0.5 \pm 5.5\%$ per decade)[1]. However, it is clear that over this latter period, the 20 year oscillation is inadequately sampled, and any bias in this sampling is likely to overwhelm any long-term trend in precipitation.

An important question concerns the most relevant climatic time-scale to which the structure and dynamics of forests respond. Forest productivity and turnover are likely to respond almost immediately to short-term interannual trends in climate. Forest mortality, in that it is driven by climatic variables rather than by internal evolution of stand structure, should also respond on similar short time-scales. Hence, the 39 year trends described here may assist in the interpretation of recent trends in forest productivity and turnover (Lewis *et al.* 2004*a*; Phillips *et al.* 2004) and perhaps net biomass change (Baker *et al.* 2004).

The datasets used in this analysis are described below.

(a) *The forest cover dataset*

We concentrate our analyses on tropical rainforest regions. The dry limits of 'rainforests' are rather arbitrary and vary according to source. We define a tropical rainforest as equivalent to the 'rainforest' and 'tropical moist forest' categories in the FAO Global Forest Resources Assessment 2000 (FAO Forestry Paper 140, data available online at http://www.fao.org/forestry/fo/fra). This assessment defines tropical forests as forests with a mean temperature in all months of over 18 °C, with 0–3 dry months (rainforests) or 3–5 dry months (moist deciduous forest), where dry months are defined as months where total precipitation in millimetres is equal to or less than twice the mean temperature in degrees Celsius. Some estimates of tropical forest area also include the 'tropical dry forest category'. However, this category frequently grades into woody savannah regions, and is excluded from the current analysis. The forest cover map was coarsened to a 0.5° resolution to be compatible with the climate dataset.

(b) *The climate dataset*

The climate dataset used for these analyses is the University of East Anglia CRU Global Climate Dataset (hereafter referred to as the CRU dataset), described in New *et al.* (1999). In this dataset the *mean climate* for the period 1960–1990 was derived from a global dataset of station climatological normals, numbering 19 295 stations for precipitation and 12 092 for temperature, and interpolated onto a 0.5° latitude by 0.5° longitude grid (New *et al.* 1999). The station data were interpolated as a function of latitude, longitude and elevation using thin-plate splines, and the accuracy of the interpolations assessed using cross validation and by comparison with other climatologies.

A gridded dataset of *monthly time series* was then constructed by New *et al.* (2000) from time-series of station data compiled by the CRU. Because the network of stations with easily available time-series data is much sparser than the network of stations with available mean climatologies, the gridded dataset was constructed using an 'anomaly' approach, which attempts to maximize available station data in space and time. In this technique, grids of monthly anomalies of temperature and precipitation relative to a standard normal period (1961–1990) were first derived. The anomaly grids were then combined with the mean monthly climatology (based on a denser station network) to arrive at fields of estimated monthly surface climate. The spatial variability in mean climate was best captured by the denser network of station normals, while temporal variability was related to broader variations in atmospheric circulation and shows a correlation over wider distances. Only stations that had more than 20 years of data available in the period 1960–1990 were used in the time-series interpolation.

An angular distance-weighted scheme was used for the interpolation of the time-series, which weights the influence of stations according to their distance from the grid cell point, and their relative angular position. The scheme used the eight nearest stations. An exponential decay function was used for the distance weighting, the decay rate being controlled by a CDD, which was set at 450 km for precipitation and 750 km for temperature (New *et al.* 2000). The CDD is defined as the distance at which the (in this case, globally averaged) inter-station correlation in time-series is no longer significant at the 95% level.

A problem for the analyses of data in the tropics in particular is the low density of the station network, particularly at the start of the time-series. This can result in several problems.

(i) As the interpolation scheme always uses the nearest eight stations, the influence radius is larger in data-poor regions. For our analysis of time-series trends in a gridded dataset, a particular problem can occur when a station is only present for part of the time in a data-poor region, and thus generates spurious interpolated trends. For example, if a station appears in a data-poor region half way through the time-series, the climate variations in that region prior to the appearance of the station are drawn from interpolation of distant stations, but then suddenly switch to being dominated by a single nearby station.
(ii) The sparseness of stations can also mean that errors in a single station's data can have a significant influence on regional estimates.
(iii) Spatial and interannual variability may be underestimated by the interpolation scheme (New *et al.* 2000).

(c) *Station density and location*

The densities of temperature and precipitation stations used in the climate interpolation are shown in figure 2. In general, the density of temperature measurements is sparser than those of rainfall. By contrast, temperature anomalies are coherent over larger distances (750 km versus 450 km for precipitation), and the overall spatial representativeness of the temperature data is therefore probably better than that of the precipitation network. In the Americas, the coverage of temperature across the Amazon basin is quite sparse, with particularly poor coverage in the Colombian Amazon and the southern Brazilian Amazon. There is little change in coverage in the 1960s and 1970s, some station dropout in eastern Brazil and southern Mexico in the 1980s and in northern and eastern Bolivia in the early 1990s. In Africa, initially there is quite dense coverage everywhere except in the DRC. In the 1970s, some stations in Angola and Cameroon drop out, as does the one remaining station in the central DRC (Kisangani). In the 1980s, there is further station drop out in the DRC and Angola, and in the 1990s in Nigeria and Ghana. In Asia, the spread of temperature stations is generally quite good, with the exception of a few areas like inland Borneo. Stations drop out in Thailand and the Philippines in the 1970s, in West Papua, southwest India and Sulawesi in the 1980s and in much of Borneo in the 1990s.

Figure 2*b* maps the precipitation stations used for the time-series analysis. The density of station data available for mean climate analysis (not shown) is considerably greater. Many of these station data do not cover the entire period between 1960 and 1998. Although some new stations appear, there is significant dropout of stations over time, which may reflect a genuine disappearance of the station, or simply that the more recent data were not available at the time of the interpolation. In the Americas, particular features to note are the appearance of a dense station network in Brazil in the 1970s and the dropout of

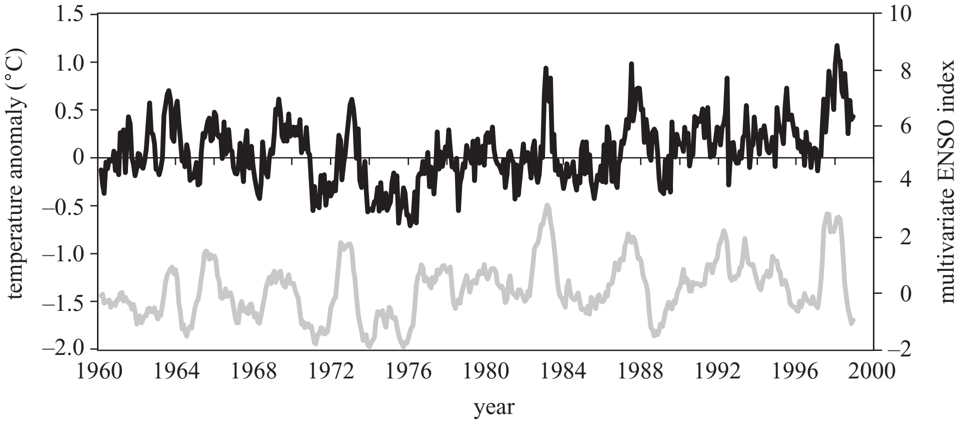


Figure 4. Time-series of pan-tropical temperature anomaly (black line) relative to the period 1960–1990, and the multivariate ENSO index (grey line).

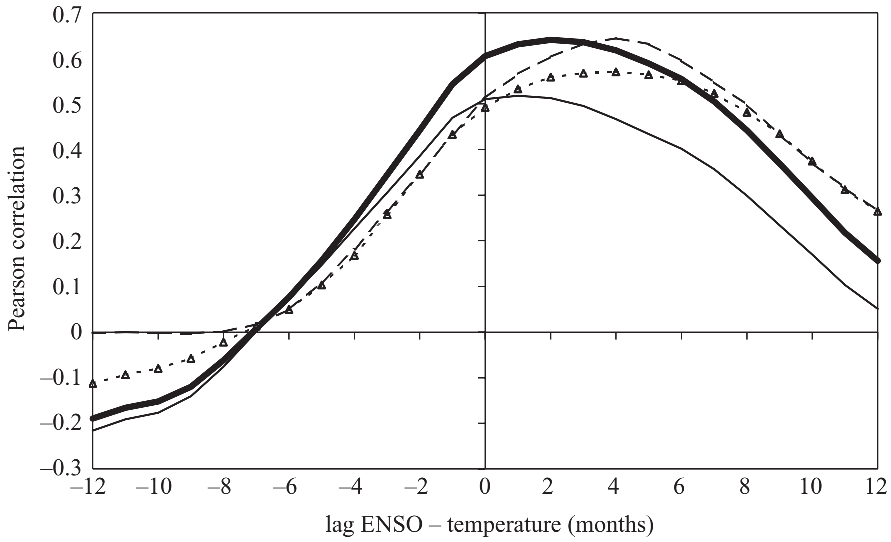


Figure 5. The cross-correlation function between mean temperature in each tropical rainforest continent (global, thick black line; Americas, thin black line; Africa, open triangles; Asia, dashed line) and the ENSO.

many stations in north Peru in the 1970s; the Guyanas, Nicaragua and Guatemala in the 1980s; Bolivia in the early 1990s, and Brazil Honduras and Suriname in the late 1990s (the later dropouts probably reflecting data availability rather than station disappearance). In Africa, the initial station network is much denser than in the Americas, with the notable exception of the DRC, which hosts by far the largest proportion of African rainforest. There was a dense network in the DRC until the early 1970s, but as this constitutes too short a time period since 1960, most of this was not used in the interpolation. As would perhaps be expected, the density of stations is correlated with the degree of forest fragmentation. In Asia, the precipitation station network is quite dense, with the exception of inland Borneo and parts of peninsular southeast Asia (Burma, Cambodia, Laos). Significant dropout of stations in the 1970s occurs in Borneo and the southern Philippines, and in the 1980s in New Guinea.

One bias that is not accounted for in this analysis is that more stations are likely to be located close to concentrations of human population, rivers or the sea, where climate conditions may be different from those of inland sites. Sombroek (2001) suggests that this may lead to a slight underestimation of rainfall in the Amazon basin. The magnitude of anomalies, as opposed to mean climates, may also be dampened by this bias.

Another potential source of bias is that urbanization may have led to local warming (the urban heat island effect) in some tropical cities, and weather stations in these cities may show disproportionately enhanced temperature trends that may bias any regional means. On the other hand, evidence exists that urban temperatures are less responsive to background temperature trends, and that this may generate a negative bias that offsets the urban warming bias (Camilloni & Barros 1997). Globally, it is estimated that any urban warming bias may enhance the measured mean temperature trend by 0.06 °C (Jones *et al.* 1999) over the twentieth century, an order-of-magnitude smaller than the observed temperature trend.

Very few studies have looked specifically at biases generated by urban heat islands in tropical forest regions. Using 14 months of hourly data between 1991 and 1992, Maitelli & Wright (1996) detected that air temperatures measured in Manaus, Brazil, were higher than the air temperature at a forest station 60 km north of the city. However, it is unclear how much of this can be accounted

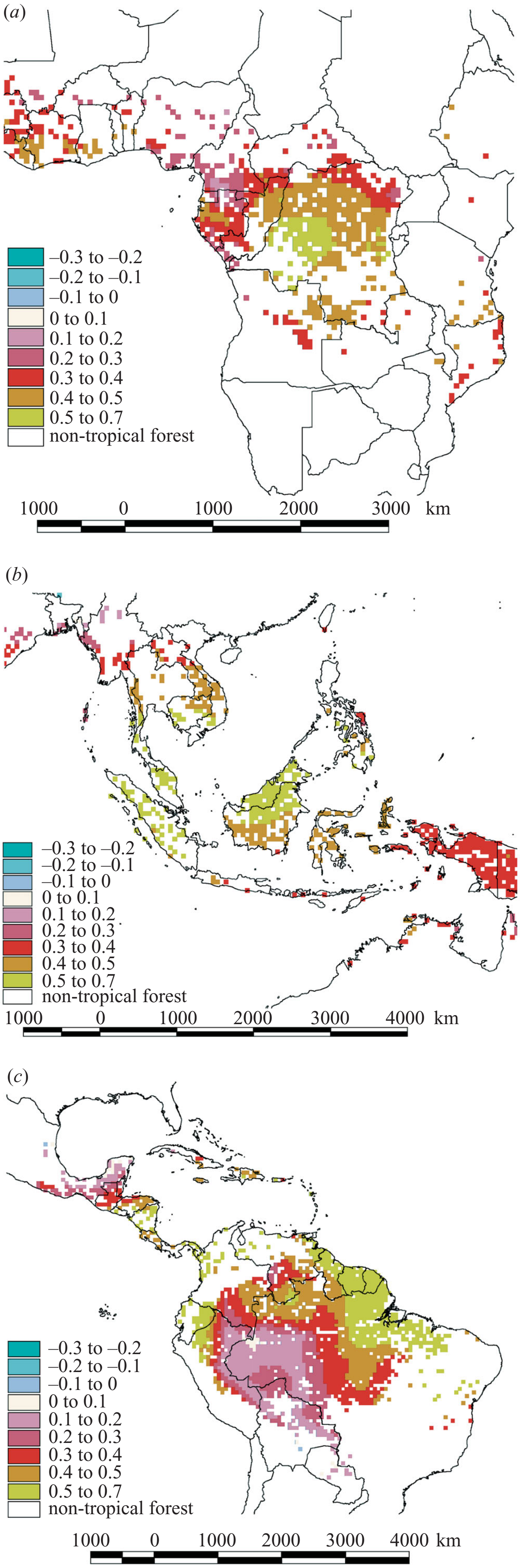


Figure 6. Maps of maximum correlation (within ± 6 months) between the ENSO index and the temperature anomaly.

for by the transition from forest to clearing causing a reduction in transpiration and a local warming (the urban station has always been in a clearing so this would not bias the temperature trends), and how much is caused by the urban heat island of Manaus. When Maitelli and Wright compared the temperature trends of major tropical Brazilian cities (Manaus, Belem, São Luis) with those in much smaller towns (Taperinha, São Gabriel da Cachoeira), no signs of disproportionate warming or major inhomogeneities were detected in the major cities. In conclusion, it is likely that there is some urban warming bias in the temperature trends, but that, regionally, this bias is likely to be moderate.

(d) *Tropical rainforest subregions*

To maintain simplicity in the summary charts we have divided the tropical rainforest area into 15 subregions (not always contiguous), which are shown in figure 3. The names ascribed to each region are convenient geographical terms, rather than referring to political entities.

(e) *A soil-water-deficit model*

In most tropical terrestrial ecosystems, a more relevant environmental control than the total precipitation *per se* is the duration and intensity of the dry season. The mean evapotranspiration rate (E) of a fully wet tropical rainforest is *ca.* 100 mm per month (Shuttleworth 1989; Malhi *et al.* 2002*a*); hence a common definition of dry season is when the precipitation (P) is less than 100 mm per month (i.e. when the forest is in net water deficit), and a common parameter for dry-season length is the number of months per year with $P < 100$ mm. However, this does not capture the importance of degrees of intensity: a dry season where P drops to 10 mm per month is more severe than one where it hovers at 90 mm per month. Similarly, many regions (particularly in Africa) experience a 'double-dip' pattern in rainfall, with two short dry seasons, which are less severe than one long dry season of equivalent total duration. Similarly, the dry-season length does not capture the importance of soil 'memory'—i.e. whether a soil is fully hydrated or only partly hydrated in the months preceding a dry month.

We develop a SWD parameter here to represent the strength and duration of the dry season, calculated from precipitation data by using a simple water balance model.

The evapotranspiration at time t (with a monthly timestep) is estimated to be a simple function of SWD. We assume that SWD varies linearly between time $t-1$ and $t+1$:

$$E = a \times \mathrm{SWD} + E_0, \tag{3.1}$$

where a (the drought sensitivity of transpiration) and E_0 (the transpiration rate in a non-moisture stressed soil) are constants, E is in millimetres per month and SWD is in millimetres. Based on eddy covariance measurements of evapotranspiration fluxes in a central Amazonian forest near Manaus, Brazil (Malhi *et al.* 2002*a*), we fix $a = -0.3625$, $E_0 = 118$ mm per month. The change in SWD in the following month is then calculated as the difference between evapotranspiration and precipitation over the month.

$$\mathrm{SWD}_{t+1} = \mathrm{SWD}_t + E_{t+0.5} - P_{t+0.5}. \tag{3.2}$$

If we assume that evapotranspiration varies linearly across a month,

$$E_{t+0.5} = 0.5\ (E_t + E_{t+1}). \tag{3.3}$$

Then the above three equations can be combined into a single equation:

$$\mathrm{SWD}_{t+1} = (\mathrm{SWD}_t \times (1 + 0.5a) - P_{t+0.5} + E_0) \times (1/(1 - 0.5a)). \tag{3.4}$$

If the soil becomes saturated, the excess rainwater is lost as runoff i.e. if $\mathrm{SWD}_{t+1} < 0$ then $\mathrm{SWD}_{t+1} = 0$. Equation (3.4) can then be fed with a time-series of precipitation data, and will output a time-series of estimated SWDs. The equation must be allowed to 'spin-up' by running the first year of precipitation data twice, so that the soils are not fully hydrated by default at the start of the first year.

It should be emphasized that the relation between E and SWD is unlikely to be applicable across all tropical rainforests because of variations in soil-water storage properties and rooting depth. For example, in drier regions the rooting depth is likely to be greater, and hence, when comparing regions, the drought sensitivity of E to SWD (i.e. the parameter a) is likely to be less than in central Amazonia. Hence, the SWD calculated here should not be considered the actual SWD, and an annual maximum value of this term will henceforth be termed the dry-season index or DSI. Nevertheless, it provides a useful measure of the *relative* variation of dry-season duration and intensity over space and time, although it probably overemphasizes the absolute range of spatial variation.

In addition, the DSI as defined here does not take into account seasonal variations and long-term trends in temperature and solar radiation, except as implicitly correlated terms for the particular central Amazonian calibration site. Any net warming trend would be expected to increase actual water stress. The DSI employed here should be thought of as a descriptor of dry-season length and intensity, rather than a measure of water stress.

(f) *Removal of seasonality and outliers, and trend analysis*

To make interannual anomalies and long-term trends clearer, the time-series data were de-seasonalized. Temperature and precipitation data for each of the 3668 grid squares lying within tropical rainforest areas were seasonally de-trended using an (ARIMA) procedure (Eurostat 2002), commonly used to seasonally adjust economic data. This procedure uses regression to estimate the value at each period in a time-series based on past values, the difference between successive periods, and a moving average. As well as examining differences and moving averages from the immediately preceding time periods, the method can also incorporate differences and moving averages from the preceding *season*. With this approach, the magnitude of any seasonal correction may thus vary over time. An ARIMA method known as TRAMO/SEATS (Gomez & Maravall 1994; Gomez *et al.* 1999) was used, which can tolerate many outlying values in a series.

Table 1. The mean climate of tropical rainforest regions over the period 1960–1998 (1960–1995 for solar radiation). (P, precipitation; S, solar radiation; T, temperature. Seasonal variation in precipitation and temperature are normalized by dividing by annual mean values.)

region	mean P (mm)	mean S ($\mathrm{MJ\ m^{-2}\ d^{-1}}$)	mean T (°C)	seasonal variation P fractional	seasonal variation S fractional	seasonal variation T (°C)	dry-season length (months)	peak DSI (mm)	s.d. peak DSI (mm)
Central America	2206	17.3	24.0	2.4	0.42	4.4	4.7	126	15.2
northwest Amazonia	2962	15.6	25.9	1.2	0.13	2.3	0.6	15	13.9
southwest Amazonia	2194	16.3	25.7	1.8	0.17	3.2	3.3	89	25.1
central Amazonia	2420	15.6	26.2	1.6	0.23	2.4	2.3	56	15.2
northeast Amazonia	2260	16.6	26.0	2.0	0.26	2.2	3.7	82	26.7
southeast Amazonia	2103	16.1	25.5	2.3	0.31	2.9	4.5	149	21.8
West Africa	1601	16.6	26.3	2.7	0.28	4.6	5.8	165	14.4
Cameroon	1782	15.2	24.6	2.1	0.18	3.0	4.3	82	13.5
north Congo	1689	17.6	24.5	1.7	0.14	2.5	3.6	104	21.4
south Congo	1530	16.5	23.8	1.8	0.26	2.7	4.3	118	12.1
southwest India	1993	18.3	25.9	3.2	0.32	4.0	5.9	148	22.7
west Malesia	2584	17.1	25.3	2.1	0.31	3.2	2.9	72	9.2
east Malesia	3094	16.7	25.4	1.4	0.18	1.6	1.2	23	15.3
Australia	1702	20.1	24.2	3.5	0.22	6.7	7.0	193	24.1
pan-tropical mean	2178	16.5	25.4	2.0	0.24	3.2	3.7	—	—

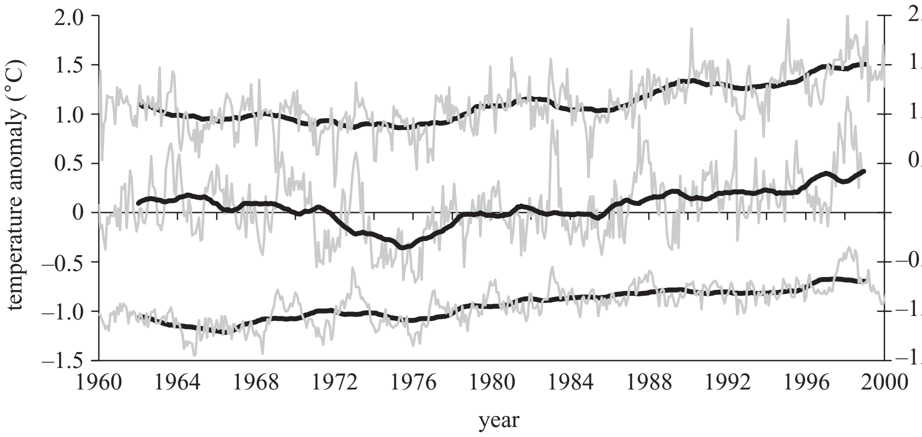


Figure 7. Time-series of the tropical rainforest temperature anomaly (centre) compared with the global (land and sea) Northern Hemisphere (top) and Southern Hemisphere (bottom) anomalies for the same period. For convenience of display, the Northern and Southern Hemisphere anomalies are displaced by +1 °C and –1 °C, respectively. The thicker lines are 4 year moving averages.

The TRAMO/SEATS seasonal adjustment procedure also identified and corrected for 'spikes' in the time-series. Outlying values were identified by examining whether the goodness-of-fit of the regression model improves significantly when one or more month's data are omitted. Where this occurs, the outlying value was estimated from past values, the difference between successive periods and a moving average.

The DSI series contains numerous zero values, making ARIMA-based seasonal adjustment more difficult. Therefore the DSI was seasonally detrended by simply subtracting the mean value for the corresponding month from each value in the series.

After seasonal adjustment of the data, the two-tailed Mann–Kendall rank statistic was used to identify trends in precipitation, temperature and the DSI in each grid square. This test statistic is commonly used in the analysis of both precipitation and temperature data (e.g. Kadioglu 1997; Kripalani & Kulkarni 2001). The Mann–Kendall rank statistic is non-parametric and so has the advantage of making no assumptions about the statistical distribution (e.g. normality) of these three variables. However, there can be significant serial autocorrelation in climatic time-series, and any simple trend test is likely to somewhat overestimate the significance levels of observed trends.

4. THE MEAN CLIMATE OF TROPICAL RAINFOREST REGIONS

The mean temperature, sunshine and precipitation in each subregion are shown in table 1. Globally, the mean annual precipitation of the tropical rainforest region is 2180 mm, the mean temperature is 25.4 °C, and the mean insolation is 16.5 GJ yr^{-1}. There is considerable variation in precipitation around this mean, with east Malesia and northwest Amazonia the wettest tropical rainforest regions with *ca*. 3000 mm of rain per year, and almost all of Africa much drier than the mean. There is less variation in mean temperature and solar radiation, although the equatorial African forests are generally cooler because of being at high elevation, and outer tropical rainforests tend to have slightly cooler annual means. For a given dry-season regime, these cooler forests suffer less water stress.

Indices of seasonality are also shown in table 1. These are defined as

$$\frac{\text{(mean annual maximum value} - \text{mean annual minimum value)}}{\text{mean annual value}}$$

for precipitation and solar radiation. For temperature, they are not normalized by dividing by the mean. For the normalized index, the value indicates the amplitude of the seasonal cycle relative to the mean.

The estimates for Australia and southwest India need to be treated with caution, as these are small areas of tropical rainforest in areas with strong spatial gradients in a climate associated with mountains. This spatial variability is probably not adequately sampled, and the 0.5° scale of the interpolated climate data may not distinguish between tropical rainforest areas and adjoining drier areas.

The spatially averaged maximum DSI for each region is shown in table 1. As would be expected, the outlying tropical rainforest regions show the greatest seasonality and dry season intensity (Australia, West Africa, southwest India, Central America), and the 'core' tropical regions the weakest dry seasons (northwest and central Amazonia, all of Malesia). However, there are significant longitudinal trends, and the core regions of tropical Africa (north and south Congo and Cameroon) are still moderately water stressed, as is northeast Amazonia. As a whole, African tropical rainforests appeared the most water stressed, and Asian forests the least. Maximum DSI is not shown for the global tropics, as the asynchrony of dry seasons across such a large area makes this a less useful term.

A plot of the maximum DSI against the dry-season length in table 1 shows a general linear relation between these two terms (not shown). Northeast Amazonia and Cameroon fall significantly below this line; here dry seasons are 'shallower' than the mean and hence the peak DSI is lower than would be expected. Southeast Amazonia falls significantly above this line and experiences more intense dry seasons than the mean.

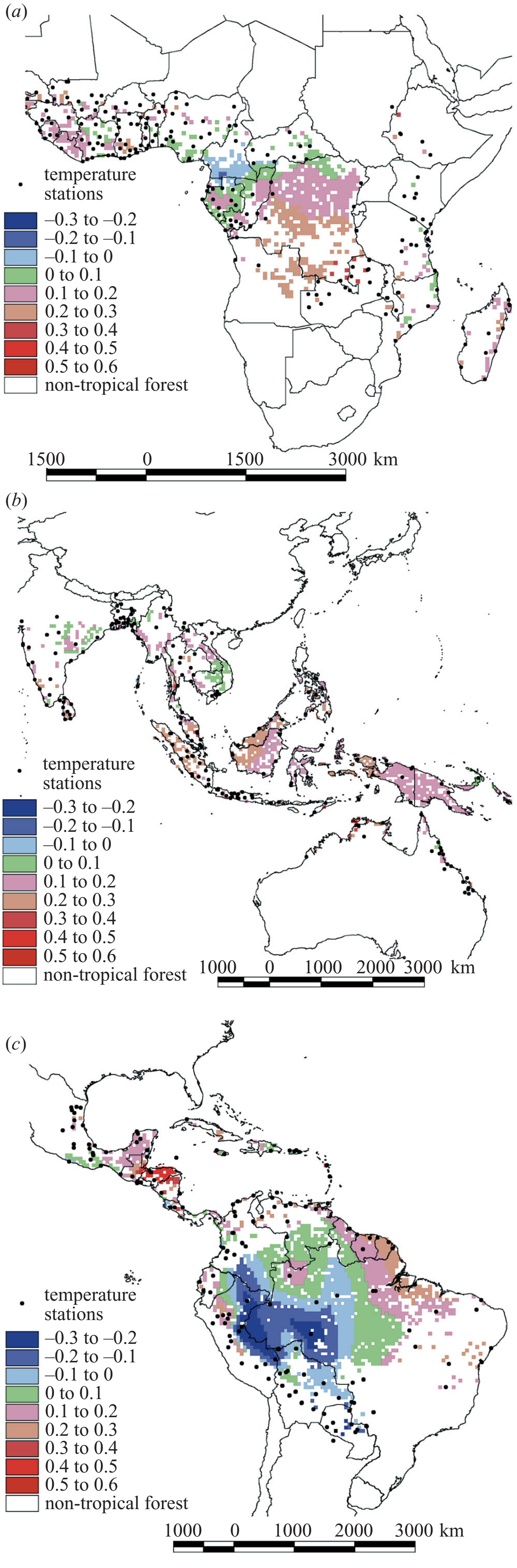


Figure 8. Maps of temperature trends over the period 1960–1998. Trends greater than 0.05 °C per decade tend to be significant at the 95% level; trends greater than 0.07 °C per decade tend to be significant at 99%, although the exact level of significance depends on the nature of the local time-series.

5. AN ANALYSIS OF VARIATION OF TEMPERATURE, PRECIPITATION AND DRY SEASON IN TROPICAL RAINFOREST REGIONS IN THE LATE TWENTIETH CENTURY: RESULTS

(a) *Variation in temperature: 1960–1998*

(i) *Interannual variability in temperature*

The pan-tropical temperature anomaly for the tropical rainforest regions for the period 1960–1998 is shown in figure 4. The multivariate El Niño index is also shown in the same figure.

Over this time-scale, the interannual variability of temperature in tropical rainforest regions is clearly greater than any net trend. This variation clearly shows a strong correlation with the ENSO, with mean temperatures *ca.* 1 °C higher during El Niño events (positive ENSO index) than during La Niña events. The Pearson correlation between mean temperature and the MV ENSO index for various lag times is shown in figure 5. Globally, the mean temperature of tropical rainforests lags the ENSO index with a mean lag time of two months, and a correlation coefficient of $r = 0.64$. The correlation is greatest in southeast Asia ($r = 0.64$, lag time four months), intermediate in Africa ($r = 0.57$, lag time four months) and least in the Americas ($r = 0.52$, lag time one month). Considering subregions, the greatest correlations are in western Malesia ($r = 0.62$, lag time three months), northeast Amazonia ($r = 0.60$, lag time two months) and southwest India ($r = 0.60$, lag time two months) (not shown), the lowest correlations are in southwest Amazonia ($r = 0.24$, lag time nil months).

Maps of the correlation between de-seasonalized temperature and the ENSO index are shown in figure 6. For each pixel, the maximum positive or negative value of the correlation coefficient within a lag window of plus/minus six months is plotted. In Africa, the strongest temperature influence is felt in the Congo basin, and in Asia across peninsular and insular southeast Asia, with a weaker correlation in New Guinea. The Americas show striking spatial gradients, with a strong ENSO influence on temperatures in northern and eastern Amazonia, and in Central America, and almost no ENSO influence in southwest Amazonia. No tropical rainforest region is cooler during El Niño events.

(ii) *Pan-tropical trends in temperature*

A simple linear trend through the global tropical rainforest temperature time-series yields a significant ($p < 1\%$) temperature trend of $+0.08 \pm 0.03$ °C per decade (i.e. a net increase of 0.31 °C between 1960 and 1998)[2]. The pan-tropical mean time-series shows a net cooling from the 1960s to 1974 (-0.08 ± 0.11 °C per decade) and a subsequent strong warming; since 1976 the net warming has been at a rate of 0.26 ± 0.05 °C per decade ($p < 0.001\%$). This post-1976 warming is observed

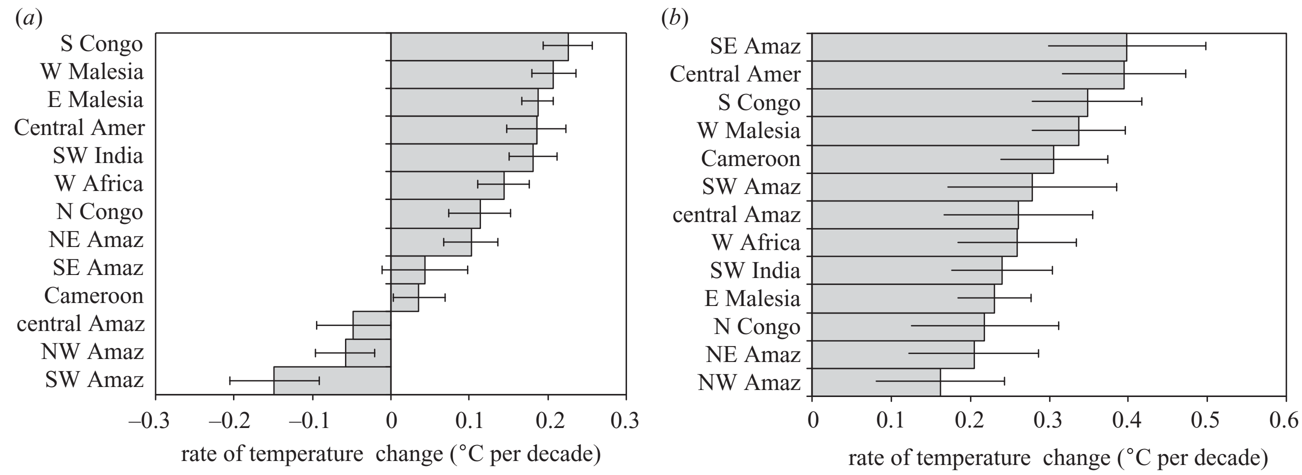


Figure 9. Bar charts of temperature trends in each tropical rainforest subregion (*a*) for the period 1960–1998; (*b*) for the period 1976–1998.

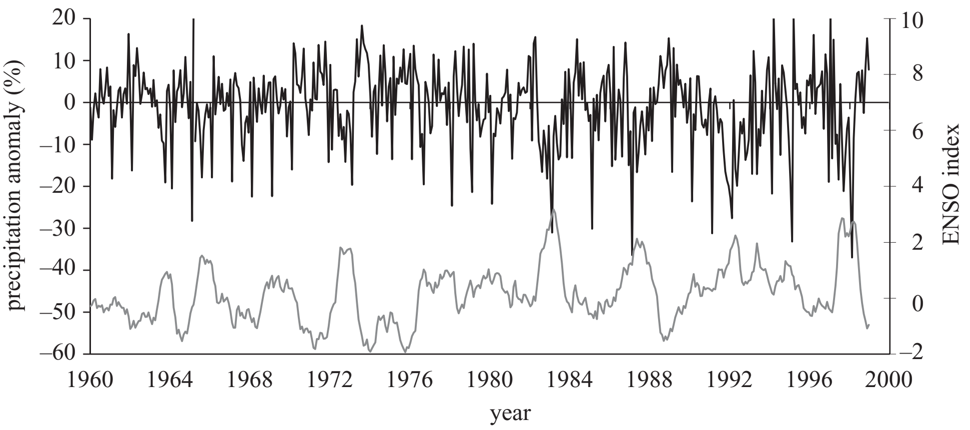


Figure 10. Monthly time-series of pan-tropical precipitation anomaly for the period 1960–1998. The percentage is calculated relative the pan-tropical mean precipitation for tropical rainforests (181.5 mm per month or 2177 mm yr^{-1}).

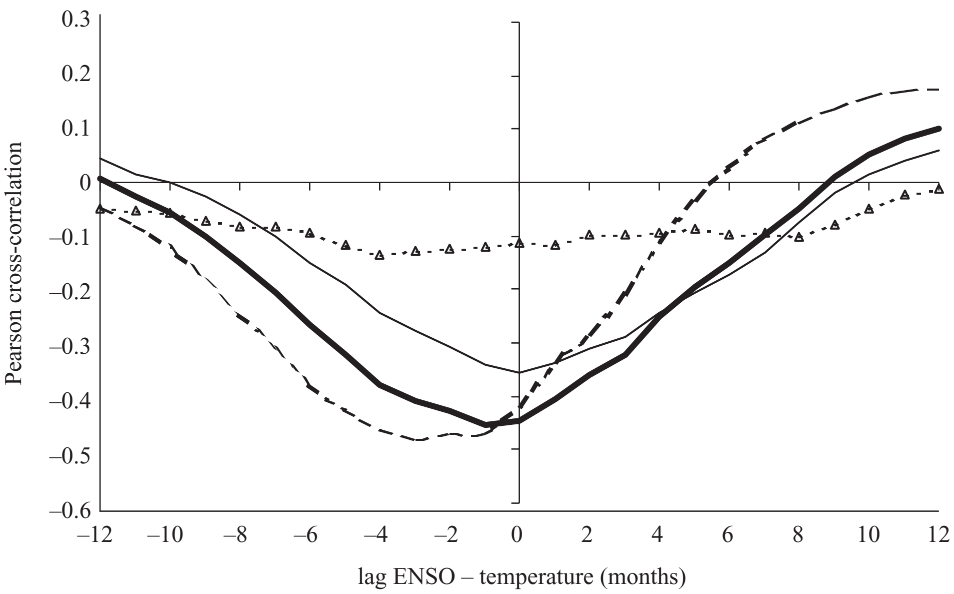


Figure 11. Cross-correlation function of the precipitation anomaly and the ENSO index for the three tropical rainforest continents (global, thick black line; Americas, thin black line; Africa, filled triangles; Asia, dashed line).

in all three major tropical rainforest regions (Americas 0.26 ± 0.07 °C per decade; Africa 0.29 ± 0.06 °C per decade; Asia 0.22 ± 0.04 °C per decade).

The results reported here are in agreement with the general trends observed by the IPCC (Folland *et al.* 2002) using a variety of climate datasets. For the tropics as a

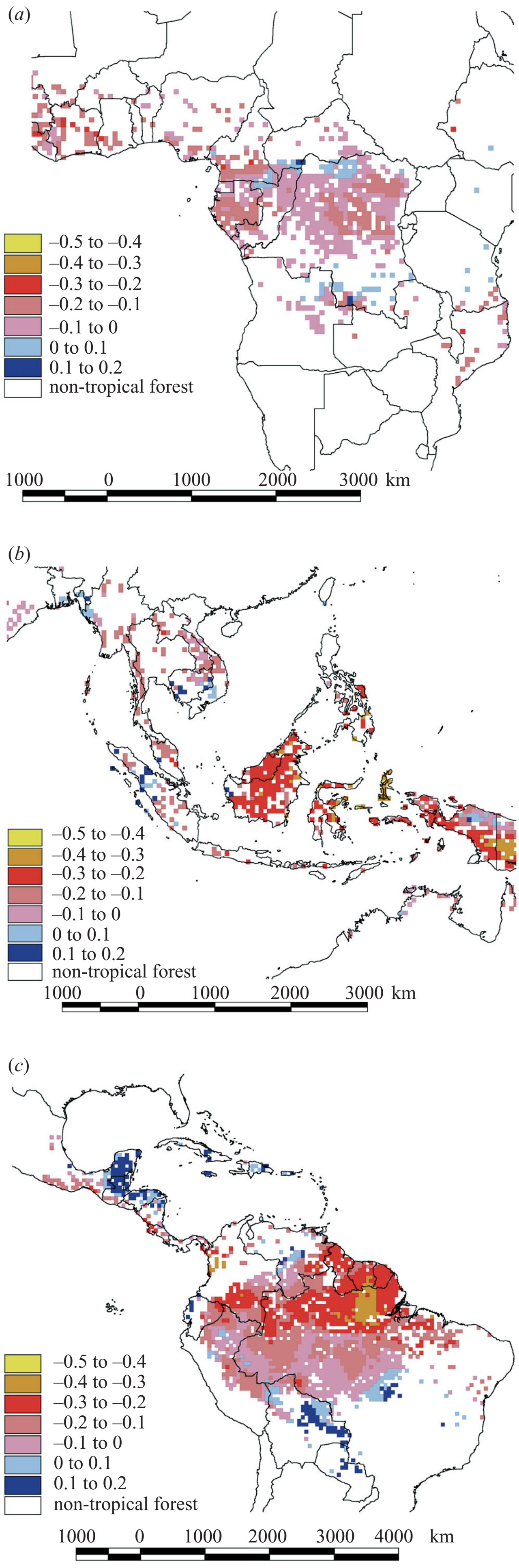


Figure 12. Maps of maximum correlation between precipitation and the ENSO index, with lag times between ± 6 months.

whole (defined in the study as all land and sea regions between 20° N and 20° S), surface temperature increased by 0.08 °C decade^{-1} between 1958 and 2000, a trend that can be divided into a cooling period from 1958 to 1978 (-0.09 ± 0.12 °C per decade) and a warming period since 1978 ($+0.10 \pm 0.10$ °C per decade). The pattern of relatively invariant or slightly cooling global temperatures between the 1940s and 1970s, followed by a rapid warming since the mid-1970s, is a feature of the global temperature pattern in both Northern and Southern Hemispheres, and the warming trend over tropical rainforests appears to fit this global pattern (figure 7). The rates of warming in tropical rainforest regions between 1976 and 1998 (0.26 ± 0.05 °C per decade) compare with a global mean land surface temperature rise of 0.22 ± 0.08 °C per decade between 1976 and 2000, and lie between the rates observed for the Northern Hemisphere (0.31 ± 11 °C per decade) and the Southern Hemisphere (0.13 ± 0.08 °C per decade) as a whole (Jones *et al.* 1999, 2003).

(iii) *Regional trends in temperature*

Figure 8 shows a map of the linear trends in temperature over the period 1960–1998. Most tropical regions show a warming trend over this period, with the notable exception of western Amazonia. The cooling in western Amazonia occurred in the early 1970s, and was followed by steady warming, and it is this cooling that causes the dip in global mean tropical rainforest temperatures over the same period. Is this cooling real, or an artefact generated by station switching? The continuity of stations in this region over the period 1960–1980 is good. Analysis of weather records from individual stations with good continuity over this period (Puerto Maldonado, Peru, 12°38′ S, 60°12′ W; Pucallpa, Peru, 8°25′ S, 74°36′ W; Manaus, Brazil, 3°8′ S, 60°01′ W) does indeed show a drop in temperatures in the early 1970s. This may be part of a longer-term oscillation: temperatures in this region were low in the 1940s, rose to a peak in the 1960s, dropped again in the 1970s and have been rising since.

Most other tropical rainforest regions show a general warming trend, with the warming accelerating since the mid-1970s. As pointed out above, the trend in the central Congo basin is less certain because of the paucity of stations and the possibility of station-switching artefacts. In southeast Asia the warming trend has been maintained across the region since the 1960s, and appears fairly homogenous across most of the region, with the greatest values in western Malesia.

The mean temperature trends in each region are summarized in figure 9, for the overall period (figure 9*a*), and the period 1976–1998 (figure 9*b*). All regions showed a net warming over the overall period except central and western Amazonia, and all regions show strong warming since 1976 of between 0.15 and 0.4 °C per decade. This is partly influenced by positive temperature anomalies of 1.0–1.5 °C during the 1983 and 1998 El Niño events, but the trend is only reduced by 0.03 °C per decade when these peaks are removed.

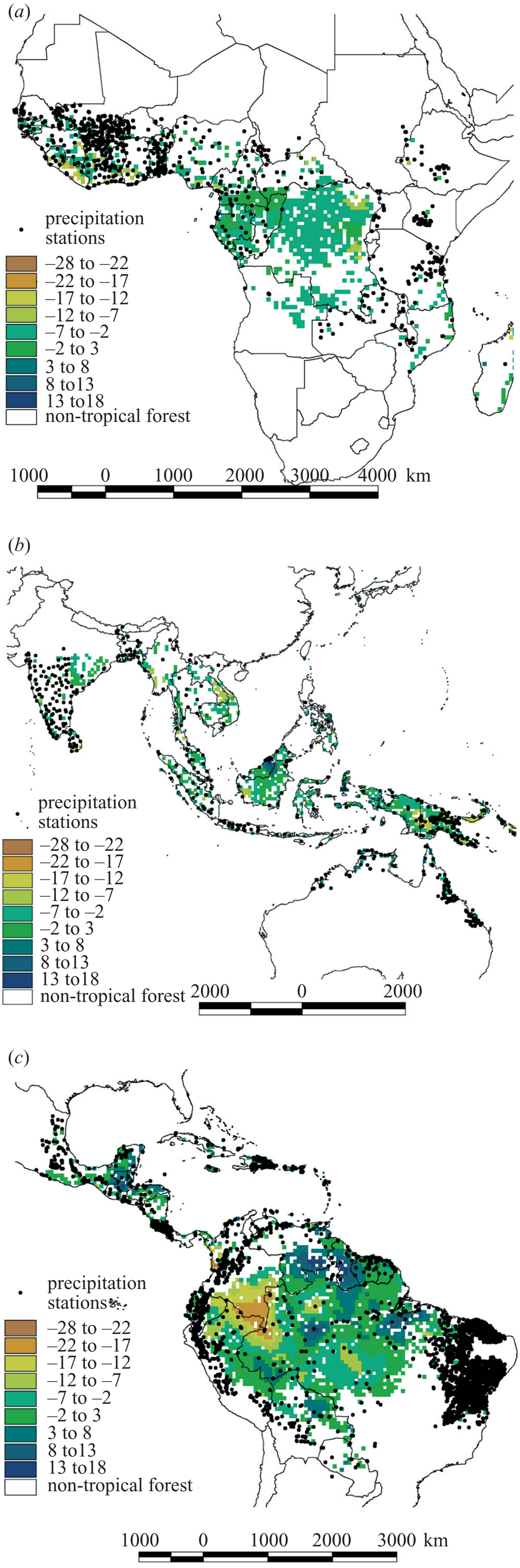


Figure 13. Maps of trends in annual precipitation over the period 1960–1998. Trends greater than 4 mm per decade tend to be significant at the 90% level, greater than 6 mm per decade at the 95% level, and greater than 7 mm per decade at 99%, although the exact level of significance depends on the nature of the local time-series.

The regional pattern of warming is similar to that reported by the IPCC (Folland *et al.* 2002; based on Jones *et al.* 1999) in global maps of temperature trends. Since the mid-1970s, all tropical rainforest regions appear to have warmed. In the period 1946–1975 what little data there are suggest moderate warming in western Amazonia, significant cooling over the Congo Basin and West Africa, and little change in southeast Asia. Hence the overall slight cooling over this period masks significant regional differences and was driven by cooling over the Congo basin.

Victoria *et al.* (1998) conducted an analysis of 17 stations in the Brazilian Amazon from 1913 to 1995, taking care to eliminate stations with discontinuities in methodologies. They report little variation in the period 1910–1940, a decade-long dip by 0.3 °C in the 1950s and a period of rapid warming since the mid-1970s at a rate of *ca.* 0.25 °C per decade. New *et al.* (2001) analysed the temperature trends for the whole African continent over the twentieth century, and observed a warming up to the 1940s, a slight cooling up to the mid-1970s and a rise of *ca.* 0.8 °C since then. Hence, the overall pattern of rapid and pan-tropical recent warming is confirmed, but in the longer-term trends, there can be significant regional differences.

(b) *Variations in precipitation: 1960–1998*

The mean monthly precipitation anomaly over tropical rainforest regions for the period 1960–1998 is shown in figure 10, calculated using the same procedure as for temperature. Compared with temperature, the precipitation record is much more variable, both spatially and temporally. The multivariate ENSO index is also shown.

(i) *Interannual variability in precipitation*

Once again, over this time-scale, the interannual variability of precipitation in tropical rainforest regions is greater than any net trend. Globally, this variation shows a reasonably strong inverse correlation with the ENSO, with less precipitation during El Niño events. This reduction in precipitation is principally caused by the warming of the eastern Pacific causing enhanced convection in this region and compensatory zones of air subsidence in northern South America and southeast Asia, which suppresses rainfall in these normally highly convective regions. The correlation between the precipitation anomaly and the ENSO index for various lag times is shown in figure 11. Globally, the mean precipitation of tropical rainforests does not lag the ENSO index (lag time zero or −1 month) and the correlation is weaker than that for temperature ($r = -0.44$, compared with $r = 0.64$ for temperature). The correlation is greatest in southeast Asia ($r = -0.48$, time lag = −3 months), intermediate in the Americas ($r = -0.35$, time lag = 0 months), and very weak for Africa ($r = -0.12$, no distinctive lag). The comparison with temperature in Africa is particularly noteworthy: although African forests are consistently warmer during El Niño events, they are not generally much drier; hence the higher temperatures are not induced by local drought, but perhaps by more general atmospheric and oceanic changes, such as increases in surface temperatures in the Indian and Atlantic Oceans. In almost every tropical rainforest region, the peak changes in precipitation precede changes in temperature, and often also precede peaks in the ENSO index.

Maps of the ENSO correlation with deseasonalized precipitation are shown in figure 12. Throughout Africa the correlation is negative but weak. It appears that some ENSOs do significantly affect tropical Africa, but the teleconnection between the tropical Pacific is variable, and appears dependent on the exact seasonal timing of the ENSO, and to what extent it influences Indian and Atlantic Ocean temperatures (Nicholson *et al.* 2000). By contrast, in both the Americas and Asia many tropical rainforest regions show a strong response to ENSO. The largest inverse correlations (reduced precipitation during El Niño events) are seen in northeast Amazonia and in a band running from Borneo to New Guinea. By contrast, many regions at the dry fringe of the tropical rainforest belt (southern and northern tips of Amazonia, northern Central America, the northern fringe of Congo and areas of southeast Asia) show a weak positive correlation, with increased precipitation during El Niño events.

Hence, a changed frequency or intensity of El Niño events would directly impact upon southeast Asian and northeast Amazonian forests, but may have little direct effect on south Amazonian or African forests.

(ii) *Trends in precipitation*

A simple linear trend through the pan-tropical anomaly time-series yields a decline in annual precipitation rates of -22 ± 17 mm per decade or $-1.0 \pm 0.8\%$ per decade ($p < 5\%$). This is a net decrease of *ca.* 86 mm between 1960 and 1998. There is little pan-tropical trend between 1960 and the mid-1970s, and a more marked decline since then. Because of the high interannual variability, the trends are generally of low significance. It should be emphasized that the trend over four decades may not necessarily be indicative of a longer-term trend. For example, our analysis of precipitation trends in one of the longest-term weather records in the tropical rainforest regions (Manaus; figure 1) showed an overall increase of precipitation at a rate of $2.6 \pm 1.2\%$ per decade, but no significant change over the period 1960–2000 ($-0.5 \pm 5.5\%$ per decade).

Separating into the three tropical rainforest continents, there is no overall significant trend in precipitation in the American tropical rainforests ($-0.6 \pm 1.1\%$ per decade), a moderately significant drying trend in Asia ($-1.0 \pm 1.1\%$ per decade; $p < 5\%$) and a strong drying trend in Africa ($-2.4 \pm 1.3\%$ per decade; $p < 0.01\%$). It is this strong drying trend in Africa that drives the overall pan-tropical decline.

Figure 13 shows a map of the linear trend over the period 1960–1998. Figure 14 shows a bar chart of precipitation trends in the various subregions. Most tropical regions show a drying trend over this period, with the exception of northeast Amazonia and Central America.

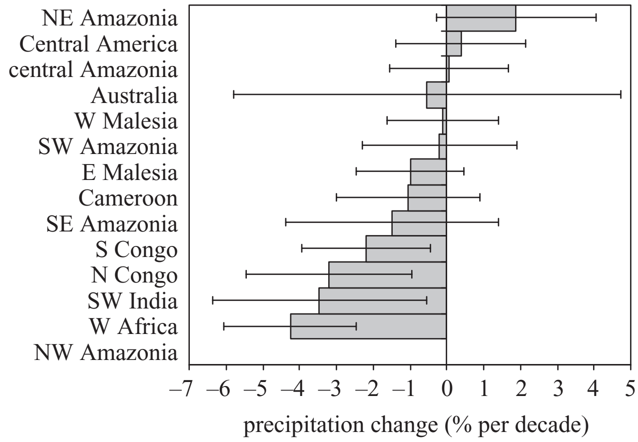


Figure 14. Bar chart of precipitation trends in each tropical rainforest subregion for the period 1960–1998. The trend for northwest Amazonia seems to be an artefact generated by the interpolation method and is not shown.

However, at a regional level the interannual variation is non-significant in many regions. The only significant trends are shown in northwest Amazonia ($-5.3 \pm 1.8\%$ per decade, but see next section), eastern Malesia ($-1.0 \pm 1.4\%$ per decade; $p < 5\%$), much of Africa (West Africa $-4.2 \pm 1.2\%$ per decade ($p < 0.001\%$); north Congo $-3.2 \pm 2.2\%$ per decade ($p < 5\%$); south Congo $-2.2 \pm 1.8\%$ per decade ($p < 10\%$)) and southwest India ($-3.5 \pm 2.9\%$ per decade; $p < 5\%$). One noteworthy feature is that the drying trends tend to be strongest in regions which are least directly affected by El Niño events, and small or even reversed in some of the El Niño-susceptible regions (Malesia, northeast Amazonia).

Are these trends real? In the Americas, suspicion is aroused by the strong drying trend inferred in northwest Amazonia, a region without weather stations and the highest precipitation rates in Amazonia. Some stations drop out of this region in the late 1970s and the interpolation scheme would then have chosen more distant (and probably drier) stations to fulfil its quota of the nearest eight stations. Analysis of records from the nearest long-term stations to this region (Iquitos, Peru, 3°45′ S, 73°15′ W; São Gabriel da Cachoeira, Brazil, 0°8′ S, 67°5′ W) reveal some evidence of a drying trend since the 1920s (-20 mm per decade annual precipitation), but no trend since the 1960s. Hence, the strong drying trend in this region shown in figure 13 is almost certainly an artefact of the interpolation technique.

In Africa, there is a widespread drying trend, with few peculiar local anomalies that would suggest artefacts or station errors. Any results from the DRC are unreliable because of the paucity of stations in this region used in this dataset, but the drying trend suggested fits into the general pattern for African forest regions. Analysis of the time-series for Africa shows that the strongest part of the drying trend is in the late 1960s and early 1970s, when data continuity was good. Hence, the trend is unlikely to be an artefact generated by station switching or station dropout.

In Asia, a modest drying trend is observed over the entire period, with few regional anomalies, again suggesting that station switching is not a major problem. Because of the interannual variability, in most areas of Africa and

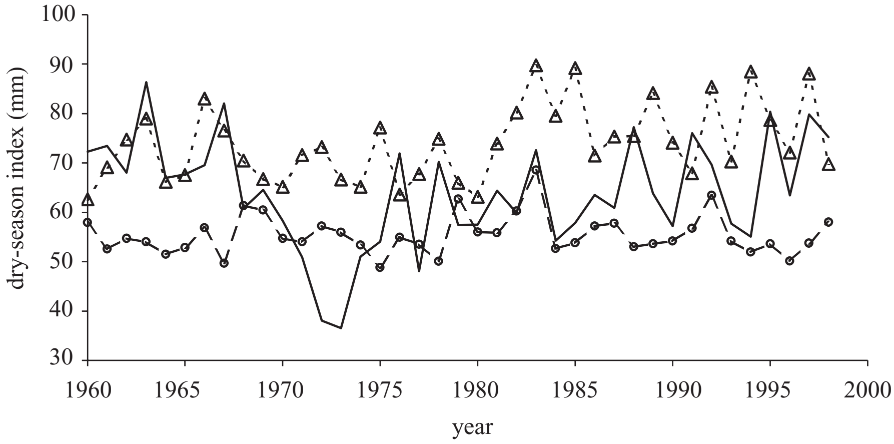


Figure 15. Time-series of the DSI over the three tropical rainforest continents (Americas, solid line; Africa, open triangles; Asia, open circles).

Asia the trends are not significant at a subregional level, but the broad spatial consistency makes the overall trend marginally significant for Asia ($p < 5\%$) and highly significant for Africa ($p < 0.01\%$).

The most noteworthy feature in the precipitation results is the strong drying trend in northern African tropics. This pattern is confirmed in a recent study by Nicholson *et al.* (2000), who examined meteorological data from a much larger dataset in Africa (1400 weather stations, including many in the Congo basin). They demonstrated a strong drying trend in northern sub-Saharan Africa, centred on major droughts in the Sahel but extending into the tropical rainforest belt of West Africa and north Congo. The drying peaked in the 1980s, when most of West Africa and the Congo basin were anomalously dry (the non-rainforest regions of east Africa, on the other hand, were anomalously wet). In the 1990s, there are hints of some recovery, particularly in the easternmost sectors (eastern Nigeria, Cameroon, Gabon) but in most regions rainfall was still well below the long-term mean. Rainfall trends in equatorial Africa appear more spatially variable, and do not show the same strong net drying. The drying trend appears to have started in the mid-twentieth century: overall in the West Africa/north Congo tropical rainforest belt rainfall levels were *ca.* 10% lower in the period 1968–1997 than in the period 1931–1960 (Nicholson *et al.* 2000).

For Brazilian Amazonia, Marengo *et al.* (1998) conducted an analysis of rainfall trends and stream-flow data. They reported regionally positive but non-significant trends in rainy seasonal rainfall in northern (Brazilian) Amazonia, similar to the results reported here for northeast Amazonia. River data from northern Amazonia indicate wetter periods in the mid-1970s, and drier periods in the 1980s. Multi-decadal climate variations in Amazonia seem to be dominating over any long-term trend in precipitation. This was also demonstrated by the analysis of rainfall in Manaus (figure 1*a*).

(c) *Strength and intensity of dry season*

The mean annual maximum DSI over the three tropical rainforest continents is shown in figure 15. Globally, there is no significant trend in maximum DSI (-0.5 ± 1.7 mm per decade). However, for DSI it is particularly important to consider local trends rather than pan-tropical averages, because of the asynchrony of the time of peak DSI in different regions. On a continental level, there is no significant trend in Asia (0.2 ± 1.2 mm per decade) or the Americas ($+0.4 \pm 3.2$ mm per decade), but there has been a moderately significant increase in dry-season intensity in Africa ($+2.8 \pm 2.0$ mm per decade, $p < 5\%$).

A map of the trends in maximum DSI is shown in figure 16, and a bar chart of trends in the various subregions is shown in figure 17. The drying trend in Africa is driven by a steady increase in dry-season intensity throughout the northern African tropics (West Africa $+7.8 \pm 3.3$ mm per decade ($p < 0.01\%$); north Congo $+9.5 \pm 5.3$ mm per decade ($p < 1\%$); Cameroon $+3.6 \pm 3.7$ mm per decade ($p < 10\%$)), perhaps slightly offset by a modest weakening of dry season in the southern Congo (-3.2 ± 3.3 mm per decade; $p < 5\%$). A similar drying trend is seen in southwest India ($+8.5 \pm 5.9$ mm per decade; $p < 1\%$). By contrast, a significant reduction in DSI in this period is indicated for the Australian tropical rainforest belt (-8.4 ± 6.4 mm per decade; $p < 1\%$). Once again, based on the limited dataset used here, the trend for much of the DRC needs to be treated with caution. However, this pattern of general drying in northern sub-Saharan Africa is clearly observed in the more comprehensive analysis by Nicholson *et al.* (2000), as is the peak in drying throughout the African tropical rainforest belt in the 1980s.

The Americas show an interesting feature in having a series of weak dry-season years in the early 1970s. This feature is apparent in most of Amazonia (southwest Amazonia 1972–1976; northwest Amazonia 1968–1972; southeast Amazonia 1972–1973; and central Amazonia 1972–1975), but in northeast Amazonia the feature is not distinguished from the usual high interannual variability (there were similar weak dry seasons in the late 1980s). Another interesting feature is seen in eastern Malesia, which generally experiences weak dry seasons (mean DSI 5–20 mm), but approximately once per decade (1965, 1972, 1982, 1998) experiences a very severe dry season with peak DSI values of 50–70 mm. The forests here need to be adapted to a generally aseasonal climate but with a once-per-decade severe dry season.

The contrast between, for example, the hydrological regimes of north Congo (steadily dry, seasonal and getting drier), Malesian (generally very wet but occasionally very

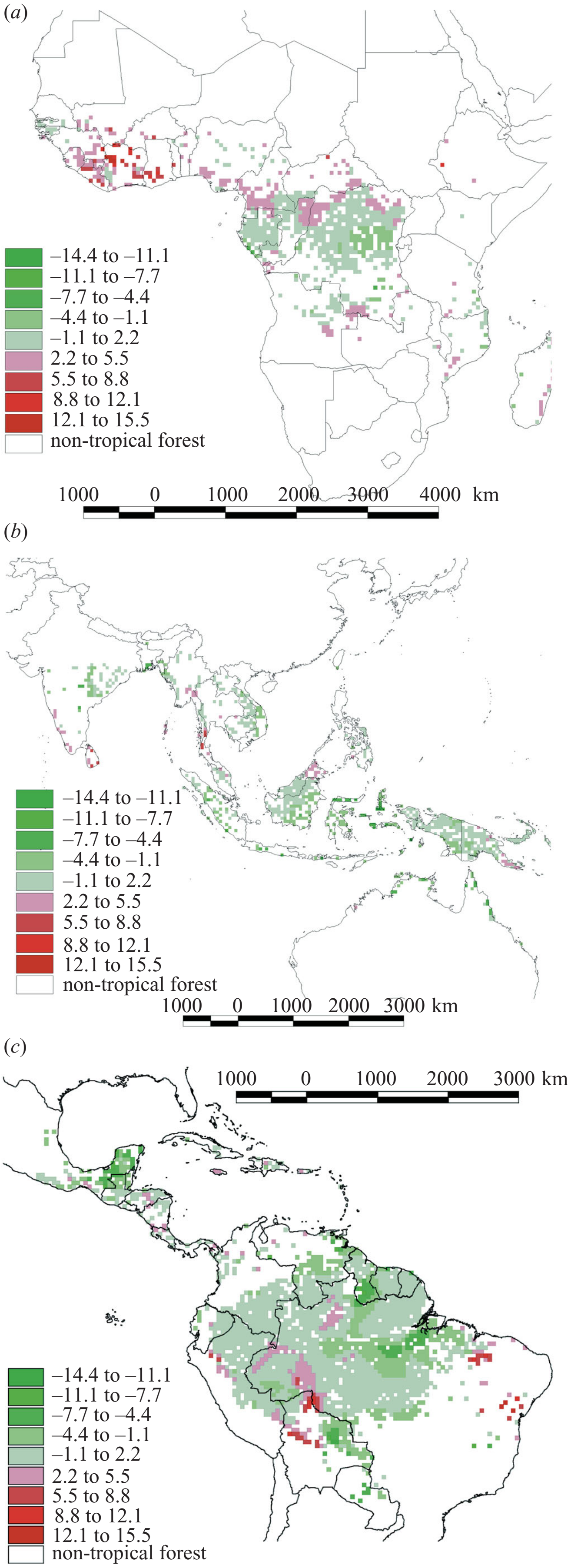


Figure 16. Maps of trends in DSI over the period 1960–1998.

stressed) and northwest Amazonian (almost always wet) tropical rainforests is marked, and suggests that successful trees in these regions need to adopt very different survival strategies.

6. DISCUSSION

The climate of tropical rainforest regions clearly exhibits considerable variation in patterns of rainfall, from no seasonality to high degrees of seasonality and interannual variability. The 'average' tropical rainforest (table 1) can be said to have an annual rainfall of 2180 mm, a dry season of 3–4 months, a mean annual temperature of 25.2 °C with a seasonal range of 3.2 °C, and a mean insolation of 16.5 MJ m^{-2} d^{-1}, but there is considerable variation, particularly in the hydrological parameters. As a whole, African tropical rainforests are generally drier, at higher elevation and cooler than those of other continents.

On an interannual time-scale, it is clear that the ENSO is the primary driver of temperature variations through most of the tropics, and of precipitation in the Americas and southeast Asia. The correlation between tropical rainforest temperature in particular and the ENSO index is remarkable. The teleconnections between ENSO and rainfall in the tropical rainforest regions of Africa are less direct, and appear to depend on the seasonal timing of events. For example, the strong El Niño of 1998 appeared to have little influence on rainfall in African tropical rainforests (Nicholson *et al.* 2000). It is noteworthy that temperature in African forests still appears to respond to the ENSO signal even when there is no precipitation response; hence the rise in temperature does not seem driven by local drought, but by a general increase in mean tropical surface temperatures.

It is also clear that climatic oscillations on multi-decadal time-scales are important in many tropical climates, and caution should be used in attributing many of the trends observed here to anthropogenic climate change. A particular example is the apparent multi-decadal oscillation in temperature in western Amazonia, a feature that was also noted by Botta *et al.* (2002). The strong drying trend in the northern African tropics may also be driven by an oscillation in Atlantic Ocean temperatures.

The spatial variability of ENSO has a bearing on questions about the frequency of large-scale disturbances in tropical rainforest regions. One hypothesis explaining the observed increase in biomass in apparently old-growth tropical rainforest plots (Phillips *et al.* 1998; Baker *et al.* 2004) is that they may be recovering from a major global disturbance in the recent past before the measurement period, with an ENSO-related drought frequently argued as the most likely culprit. However, the strongest El Niño events of the twentieth century have occurred only recently (1982–1983 and 1997–1998)[3]. If forests have gained biomass over these events, it is unlikely that they generally lost substantial biomass earlier in the century through an El Niño-related drought. Moreover, rates of biomass gain would be expected to be higher in El Niño-affected regions (northeast Amazonia, Malesia) than in others (e.g. southwest Amazonia). This is not the case.

A substantial and rapid warming of *ca.* 0.26 °C per decade is evident in all tropical rainforest regions since the mid-1970s. The recent rise is highly significant and global in extent: the net increase of *ca*. 0.6 °C in recent decades is comparable to the amplitude of temperature oscillation induced by the ENSO. This feature is remarkable, independent of its cause, and perhaps not noted sufficiently in discussions of century-long trends: on the physiologically relevant time-scale of years to decades, tropical rainforests have recently experienced rapid warming. The pan-tropical extent of this rise argues against it being induced by a local climatic oscillation or by local land-use-change effects. This trend since the 1970s seems synchronous with and consistent with changes in the global climate over the same period that have been ascribed to the anthropogenic greenhouse effect (IPCC 2002). It thus seems likely that this recent trend is indeed a signal of the anthropogenic greenhouse effect. If so, climate models suggest that a warming of between 2 and 5 °C can be expected in tropical rainforest regions over this century (Hulme *et al*. 2001; Giorgi 2002; Cramer *et al*. 2004), a change that seems likely to have a substantial impact on tropical rainforest physiology (e.g. Cowling *et al*. 2004).

There is much greater uncertainty about how tropical precipitation regimes will respond to changes in the global atmosphere. Globally, evaporation rates are expected to increase, the atmosphere is expected to become more humid and rainfall rates to increase. Indeed, satellite observations of upper-tropospheric humidity from 1980 to 1997 show statistically positive trends of 0.1% per year for the zone 10° N to 10° S. However, any pan-tropical trends in precipitation are expected to be eclipsed by strong regional variations as atmospheric circulation patterns shift. There is little agreement among climate models as to the future pattern of rainfall in the tropics.

The results presented here confirm that, in contrast to the pattern with temperature, regional trends in precipitation and dry-season intensity do indeed dominate over any coherent pan-tropical trend. The high interannual variability of precipitation makes it difficult to detect any overall trend in the American tropics, but there is a hint of a marginally significant drying trend in the Asian tropics. In African tropical rainforest regions, however, the drying trend is very strong, particularly at the northern edge of the tropical rainforest zone. This trend appears to be associated with the general drying of the Sahel region in the second half of the twentieth century. Driven mainly by the trend in Africa, overall precipitation levels in tropical rainforest regions seem to have declined in recent decades ($-1.0 \pm 0.8\%$ per decade; $p < 5\%$). This contrasts with the general expectation that precipitation levels will increase with global warming. However, the net pattern of precipitation change projected for tropical rainforests (typically between -1 and $+2\%$ per decade; Giorgi 2002) is highly dependent on the spatial pattern of projected drying. The current drying trend may continue, or it may simply reflect natural oscillations, and reverse in coming decades. However, a recent analysis (Giannini *et al*. 2003) suggests that the drying in the Sahel (and hence probably the entire northern African subtropics) is driven mainly by the general warming trend in the Indian Ocean and tropical Atlantic Ocean, which has weakened the African monsoon. Hence this African drying may indeed be a signal of the anthropogenic greenhouse effect.

The drying of specific tropical regions seems to be decoupled from the recent pan-tropical warming. Regions

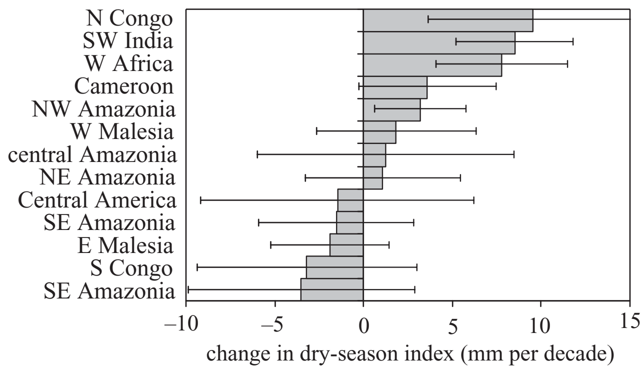


Figure 17. Bar chart of trends in DSI for each tropical rainforest subregion for the period 1960–1998.

that have not experienced drying (e.g. Amazonia) show similar rates of temperature increase to regions that have (e.g. Africa).

A frequently cited climate modelling scenario (Cox *et al*. 2000; Cowling *et al*. 2004) suggests that northeastern Amazonia may be vulnerable to extreme drying in response to circulation shifts induced by global warming, and that the consequent die-back of tropical rainforest could substantially accelerate global warming. So far, there is little evidence of any drying trend; in fact, the region has become marginally wetter (precipitation trend $+1.9 \pm 2.2\%$ per year; $p < 10\%$; no significant trend in DSI). However, this region is strongly influenced by the ENSO; if the ocean–atmosphere system were to shift into a sustained 'El Niño-like' state in coming decades (as opposed to the ENSO simply increasing in frequency and amplitude), the region could be vulnerable to drying.

The apparent marginality of Africa's tropical rainforest zone stands out in this analysis. This is the driest tropical rainforest region, and in recent decades it has generally become drier. The extent of African tropical rainforest seems particularly vulnerable to small shifts in ocean–atmosphere circulation. The palaeo-record seems to confirm this: large areas currently covered by African tropical rainforest appear to have been covered by savannah in the last Ice Age (Morley 2001), and perhaps as recently as 2500 years ago, contrasting with the continuity of forest cover in most of Amazonia (Mayle et al. 2004).

With some caveats about biogeographical and palaeohistorical differences between regions, it appears that a study of how African forests have responded to the drying trends of recent decades may yield useful insights into how tropical rainforests in general may respond to future drying. If eastern Amazonia were to dry over this century, perhaps we can gain insights into the future of its surviving forests by examining what happened to Africa's forests over the last decades of the past century?

Finally, the phrase 'surviving forests' is important to keep in mind. The most important process to affect the northern African tropical rainforests over recent decades was probably not the reduction in rainfall, but fragmentation and clearance. The long belt of tropical rainforest at the southern edge of West Africa now largely consists of small, logged-over fragments. Climate and deforestation are coupled, in that drier regions are more likely to be deforested, and deforestation contributes to modifying local and global climate. The fate of many of the world's tropical rainforests will probably not be primarily determined by climate trends, but by human actions on forest use or protection.

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ENDNOTES

[1]All uncertainty estimates in this paper are reported as twice the standard error, corresponding to approximately 96% confidence for a normal distribution.
[2]All significance values calculated in this manuscript are estimated from the two-tailed Mann–Kendall rank statistic.
[3]There is some evidence, however, of a strong El Niño-associated drought in much of Amazonia in 1925.

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GLOSSARY

ARIMA: autoregressive integrated moving average
CDD: correlation decay distance
CRU: Climate Research Unit
DRC: Democratic Republic of Congo
DSI: dry-season index
ENSO: El Niño–Southern Oscillation
SWD: soil-water deficit